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RADIATIVE TRANSFER IN THE OXYGEN A-BAND AND ITS APPLICATION TO CLOUD REMOTE SENSING

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ABSTRACT. Detection of clouds and retrieval of their properties (top and bottom altitude, optical thickness) with satellite-based spectrometers needs the solution of radiative transfer in the atmosphere. Depending on the application needed for and instrument capabilities, a trade-off choice has to be made between accuracy and speed. This study aims to characterise the range of applicability of analytical asymptotic equations to real scenarios. It has been found that the errors, introduced with approximate parameterisations, are within reasonable ranges both in absolute and relative values.

1. Introduction

Modern algorithms for cloud detection and characterisation make use of the oxygen A-band absorption in the visible portion of the electromagnetic spectrum (758–772 nm). Different approaches have been taken, when radiative transfer in the atmosphere is calculated, each with its advantages and drawbacks. Exact solutions of full radiative transfer can be employed if 3D effects are sought. This approach ensures high accuracy to detriment of computational speed and storage. On the other hand, if on-the-fly forward calculations are needed for operational use, approximate relations for the 1D scalar case have to be deployed. This makes possible to avoid the commonly used look-up-table approach.

2. Approximate asymptotic equations

When a cloud is idealised as a perfect reflector, light incident on the cloud top will be scattered back and will not be absorbed by the oxygen underlying the cloud nor by oxygen molecules inside the cloud. So the depth of the absorption line near 760 nm decreases as the cloud altitude increases. In order to exploit this spectral feature, the top-of-atmosphere (TOA) reflectance is parameterised with the following relation

$$R_{\mathrm{TOA}} = R_0 + T_1 R_b T_2 \tag{1}$$

where R_0 gives the reflection function of the part of atmosphere above the cloud (with account for both gaseous and particle scattering and absorption, in the single scattering approximation), R_b is the reflection function of the cloud-underlying atmosphere system

together with surface contribution. The functions T_i $(i = 1, 2)$ give the transmission coefficients from the sun to a cloud and from the cloud to a satellite, respectively, accounting for multiple photon scattering, gaseous and aerosol reflection and absorption. Explicit equations are given elsewhere [1]. It is also well known [2] that reflection R_{TOA} can be written as

$$R_{\mathrm{TOA}}(\mu, \mu_0) = R_{\infty}(\mu, \mu_0) - t\, K_0(\mu) K_0(\mu_0) + \frac{A\, t^2\, K_0(\mu) K_0(\mu_0)}{1 - A\,(1 - t)} \tag{2}$$

where t is the diffuse transmissivity and A the surface albedo. $K_0(\mu)$ and $K_0(\mu_0)$ are the escape functions, μ and μ_0 the cosine of viewing and solar zenith angles and R_{∞} the reflection function of an infinite layer, respectively. The escape function is defined as

$$K_0(\mu) = \frac{3}{7}(1 + 2\mu)$$

and can be approximated with an accuracy of 2% [3]. The relation between t and the cloud optical thickness τ is given by [4]

$$t = \frac{1}{1.07 + 0.75\, \tau\, (1 - g)} \tag{3}$$

in the part of the spectrum where no absorption takes place (758 nm) and there is no sensitivity to cloud altitude. Solving the equation (2) for the quantity t, one derives

$$t = \frac{D(1 - A)}{1 - A(1 + D)}, \qquad D = \frac{R_{\infty} - R_{\mathrm{TOA}}}{K_0(\mu) K_0(\mu_0)} \tag{4}$$

which enables the calculation of cloud optical thickness. It has been shown [5] that the error of the above presented analytic equations does not exceed 5% for clouds at $\tau > 5$ and solar zenith angles $< 75°$, therefore ensuring the applicability to real scenarios.

3. Broken cloudiness

Moving toward operational processing, horizontal variability of clouds has to be taken into account. Instruments with a coarse spatial resolution (as GOME-1 or SCIAMACHY) will register mixed contributions to observed reflectances R_{obs} due to broken cloud scenes. To reduce the influence of light scattered back by surface, the independent pixel approximation (IPA) [7] has been employed and partially cloudy scenes (i.e. $c_f < 1$) are scaled to fully cloudy cases ($c_f = 1$) using

$$R_{\mathrm{obs}} = c_f R_c + (1 - c_f) R_s \tag{5}$$

where c_f and R_{s} stand for cloud fraction and clear sky reflectance, respectively.

4. Cloud top and bottom height retrieval

The cloud reflectance R_c, obtained with equation (5), is a function of cloud top height h and geometrical thickness l. It has been shown [1] that it is also linear in h and it can be Taylor-expanded with

$$R_c = R(h_0) + \frac{\partial R}{\partial h}(h_0)(h - h_0) \tag{6}$$

where h_0 is chosen equal to 1 km (typical for low level clouds). Therefore, having at hand the measured spectral R_c, the values of the forward calculated TOA reflectance R, its derivative R' and τ, the pair (h, l) is retrieved, minimising the cost function

$$\|R_c - R(h_0) - R'(h_0)(h - h_0)\|^2 \tag{7}$$

where arguments in the functions are omitted for simplicity.

Using the above set of equations, the shown errors (defined as $\text{VALUE}_{ret} - \text{VALUE}_{true}$ with respect to exact radiative transfer solutions) in Figures 1 and 2 have been found, for typical values of surface albedo, ranging from black surface (water) to vegetation.

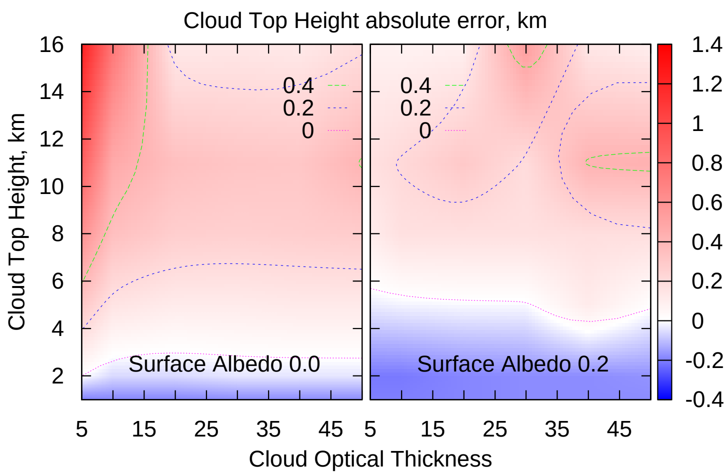

Figure 1: The error in cloud top height retrieval. $c_f = 1$ is assumed. Input parameters: water cloud, cloud geometrical thickness 1 km, droplet effective radius of 6 μm, gamma particle distribution. Geometry: solar zenith angle 60° and nadir view.

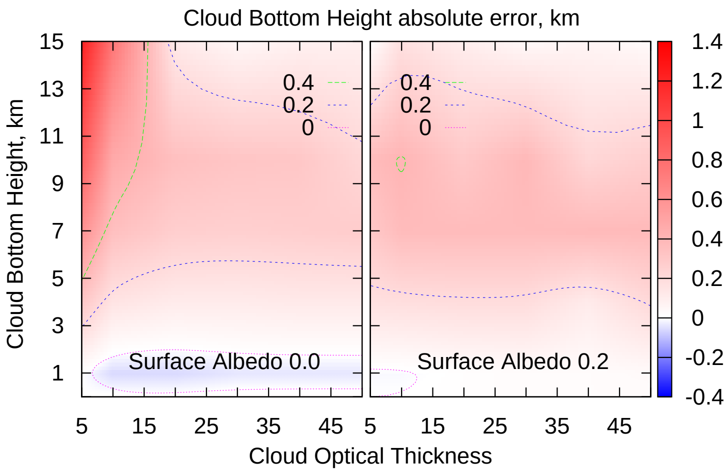

Figure 2: The error in cloud bottom height retrieval. Same parameters as in Figure 1.

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